Article
Chinese Science Bulletin
Atomic & Molecular Physics
June 2013 Vol.58 No.16: 1876–1881
doi: 10.1007/s11434-013-5789-z

Distribution of populations in excited states of electrodeless discharge lamp of Rb atoms

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Received September 29, 2012; accepted January 5, 2013

The intensity of fluorescence spectral lines of Rb atoms in the region of 350–1110 nm is measured in eletrodeless discharge lamp. The population ratio between the excited states is calculated according to the spontaneous transition probabilities with rate equations. At the same time, the population density of energy level is also obtained. The results provide the potential applications of electrodeless discharge lamp in atomic filter and optical frequency reference at higher excited states without a pumping laser.

electrodeless discharge lamp, population ratio, population density

Citation: Tao Z M, Wang Y F, Hong Y L, et al. Distribution of populations in excited states of electrodeless discharge lamp of Rb atoms. Chin Sci Bull, 2013, 58: 1876–1881, doi: 10.1007/s11434-013-5789-z

The electrodeless discharge lamp of Rb atoms containing Rb vapor and buffer gas is an important component of the microwave Rb atomic clock [1,2]. Nowadays, they play a central role in applied physics and analytical chemistry [3,4], metrology such as the Rb atoms frequency standard and alkali magnetometer [5]. The reason why the lamp has been used for optical pumping [6] instead of lasers in these devices is mainly that the electrodeless discharge lamp can yield fluorescence with stable frequency and higher signal-to-noise ratios [7]. The fluorescence of the electrodeless discharge lamp can also be used as a pumping light source for active optical clock [8,9], multi-threshold second-order phase transition [10], and Faraday anomalous dispersion optical filter [11].

In recent years our group has begun a series of experiments to investigate the population distribution of some main excited states of the electrodeless discharge lamp [12]. In this work, we discuss the experiments and results investigating the distribution of excited states from visible light to near-infrared in the region of 350–1110 nm.

1 Experimental setup

As shown in Figure 1, the bulb in lamp is a cylindrical glass cell with a length of 3 cm and a diameter of 3 cm. It contains natural Rb atoms and Xe gas at 2.7×10^2 Pa, the bulb is supplied with 178 MHz rf (radio frequency) power and can be heated from room temperature to 200°C. The lamp is designed to output light from both sides of the bulb, so a laser beam could pass through the lamp. The USB2000+ spectrometer produced by Ocean Optics Company in USA with a resolution of 1.5 nm is used to measure the fluorescence spectra.

When heating voltage is set to10 V, about 20 min later, the temperature of lamp is heated from room temperature to 120°C. At the moment, rf is switched on. When rf voltage reaches 8 V, the lamp lights. At this time, the lamp is working at the red mode.

After electrons and ions of the lamp containing Rb atoms

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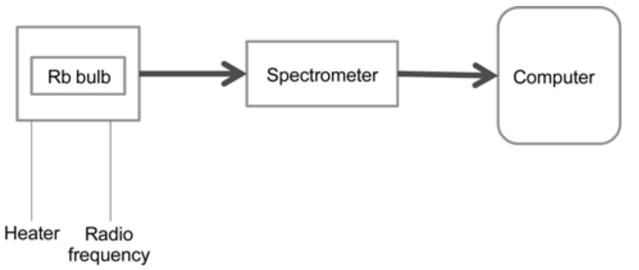

Figure 1 The experimental scheme for spectrum research of Rb electrodeless discharge lamp.

and Xe atoms are accelerated by the high frequency electric field, their energy increases [1]. These electrons and ions with high energy are collided with Xe atoms. More electrons and ions are produced. These electrons and ions with high energy excite Xe atoms to high level. When Xe atoms transit from high level to low level by spontaneous radiation, they can release the fluorescence. At that time, the spectra of Xe atoms appear using the spectrometer. If these Xe atoms in excited states are collided with Rb atoms, energy can be transferred from Xe atoms in excited states to Rb atoms. Xe atoms go back to ground state through no radiation transition when they excite Rb atoms from ground state to excited states. Similarly, when Rb atoms transit from high level to low level by spontaneous radiation, the spectra of Rb atoms appear.

As there are Xe atoms in the Rb bulb, the spectra measured are divided into two parts. One is the spectra of Rb atoms which is just the subject investigated in this work. The other is the spectra of Xe atoms which is not the subject investigated here. Therefore, in this paper, we do not consider the fluorescence spectra of Xe atoms.

2 Results

2.1 Intensity of spectral lines of Rb atoms

The lamp can operate in three spectral modes. They are the ring mode, the red mode and the weak mode respectively [12]. When changing the rf power from low to high, the weak, the red and the ring modes appear in sequence. No matter which mode the lamp is operating in, the population ratio between the excited states of Rb atoms is almost constant. For simplicity, we do not consider the working mode when the intensity of fluorescence spectral lines of Rb atoms is measured.

Figure 1 shows the block diagram of our experimental arrangement, and Figure 2 shows the energy diagram of the transitions related to the spectral signal. The energy levels of Rb atoms that we need to measure are located in the region of 350–1110 nm. We pay special attention to transition between the excited states on the blue-green band, which can be used to realize submarine communication, underwater communication. In order to facilitate reference, we draw other energy levels of Rb atoms.

The intensity of different spectral lines of Rb atoms varies widely, of which 780 nm is the strongest, 795 nm is ranked second and 520 nm is the weakest in our measurements. As the intensity of spectral lines measured by spectrometer is

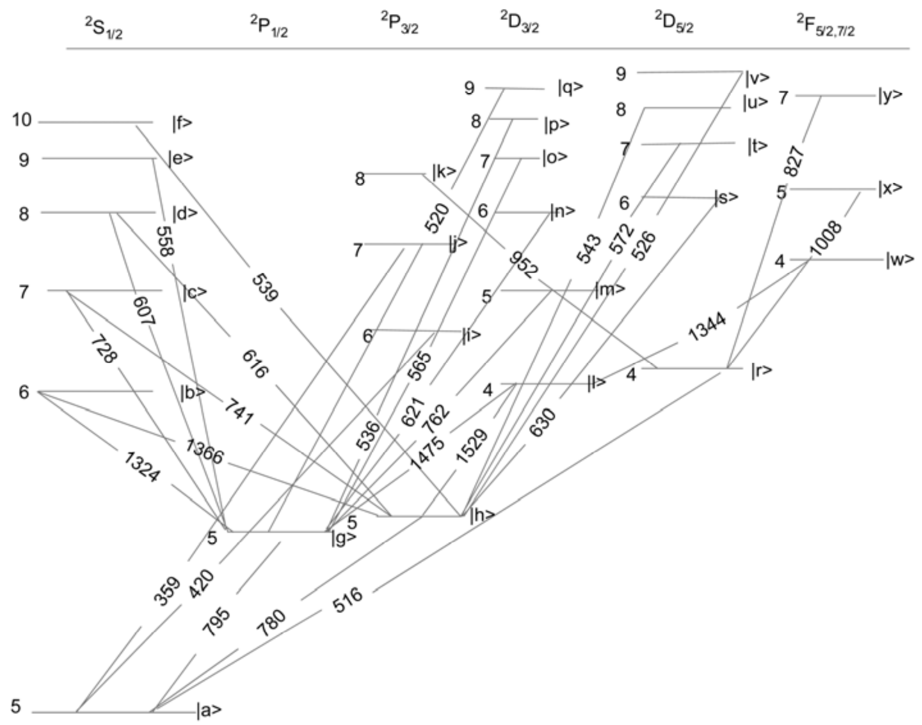

Figure 2 The energy level diagram of the transitions.

limited, when the intensity of 780 nm is close to saturation, that of 519 nm is still very weak and almost invisible. So it is necessary to measure the intensity of spectral lines group by group. For the same lines, the intensity of spectral lines varies with distance between the spectrometer and rubidium lamp. In order to compare the intensity of spectral lines, they are converted in accordance with the intensity value of 780 nm. The following several spectra are measured according to different precision.

When the distance between the probe of spectrometer and Rb lamp is set appropriately, the relative intensities of 780, 795, 883 nm can be detected (Figure 3). Their relative intensities in arbitrary units are 61709, 51131, 5006, respectively. As shown in the Figure 3, the relative intensity of 780 nm is the strongest, 795 nm is ranked second and 883 nm is ranked third. 420 nm is next to 883 nm, which is not assigned to the spectrum line of Rb atoms and is used for the reference intensity.

Figure 4 shows that the relative intensity of the 420 nm can be calculated according to the relative intensity of 883 nm. The relative intensity of 420 nm is 1385.

As shown in the Figure 5, the relative intensities of 572, 616, 621, 630, 728, 741 and 762 nm are 181, 153, 316, 550, 236, 357, 657, respectively according to the relative intensity of 420 nm.

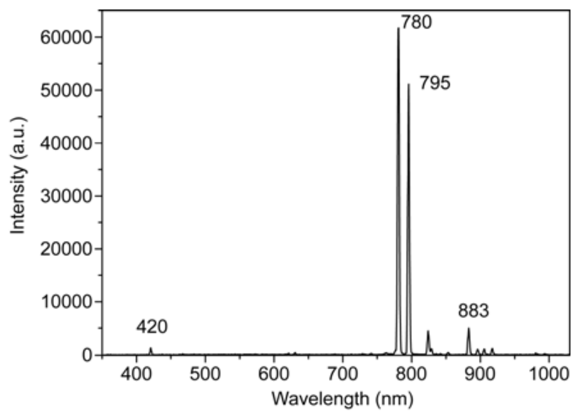

Figure 3 The intensity of 420, 780, 795, 883 nm.

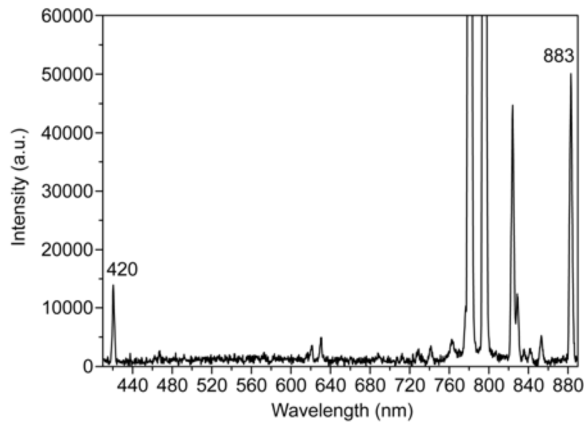

Figure 4 The intensity of 420, 883 nm.

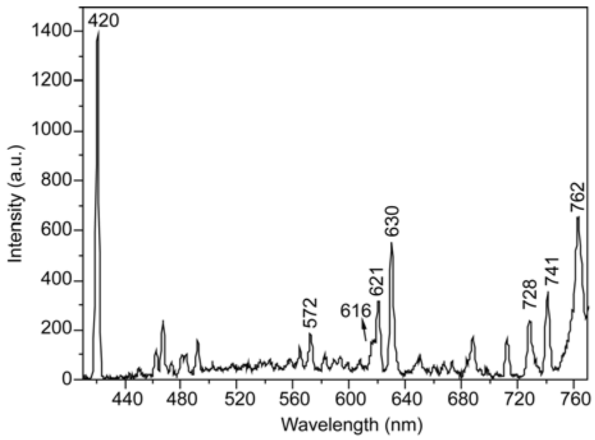

Figure 5 The intensity of 420, 572, 616, 621, 630, 728, 741, 762 nm.

The relative intensities of the other spectra lines can be measured in the same way. Figure 6 shows that the relative intensities of 827, 836 nm can be obtained by the relative intensity of 762 nm. Their relative intensities are 2724, 326, respectively.

As shown in Figure 7, the relative intensities of 516 nm can be obtained by the relative intensity of 616 nm. The relative intensities of 516, 520, 526, 536, 539, 543, 558, 565 and 607 nm are 31, 14, 29, 51, 31, 77, 57, 144 and 88, respectively. Likewise, Figure 8 shows that the relative intensity of 359 nm can be obtained by the relative intensity of 516 nm. The relative intensities of 952, 1008 nm can be obtained by the relative intensity of 836 nm (Figure 9). The relative intensities of 359, 952 and 1008 nm are 61, 62 and 88, respectively.

Table 1 lists all the spectra measured. In column 1, the spectral intensities are listed with different wavelengths, and they are listed by their relative intensities in column 3 of Table 1.

2.2 Population ratio between excited states calculated by rate equations

The corresponding reduced oscillator strengths are calculated

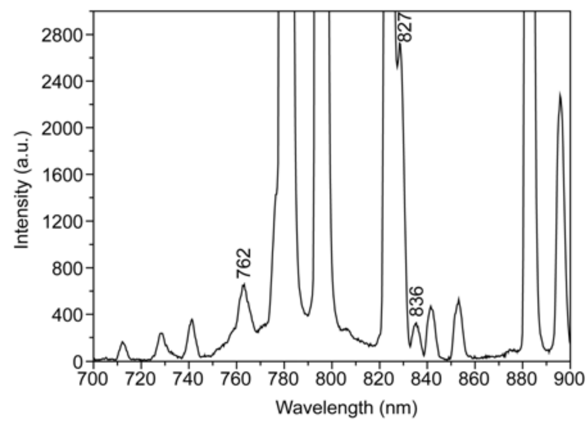

Figure 6 The intensity of 762, 827, 836 nm.

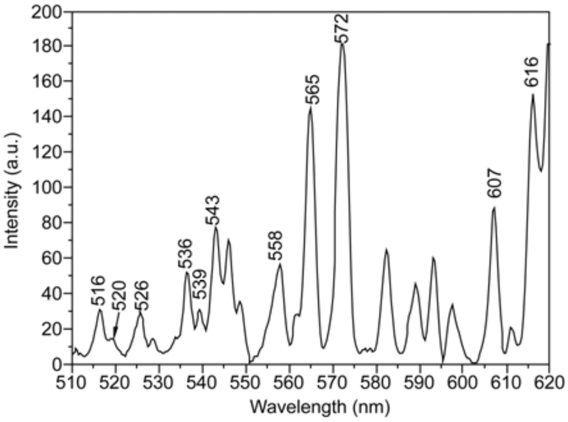

Figure 7 The intensity of 516, 520, 526, 536, 539, 543, 558, 565, 572, 607, 616 nm.

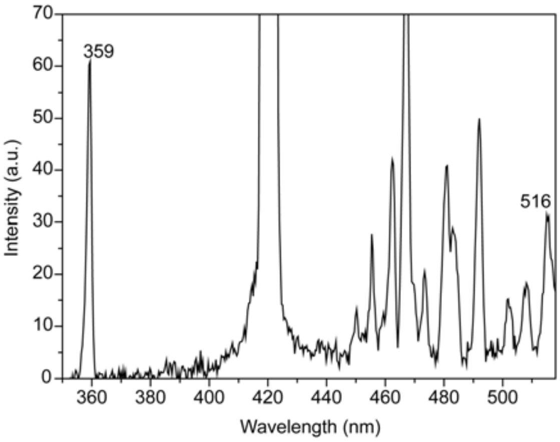

Figure 8 The intensity of 359, 516 nm.

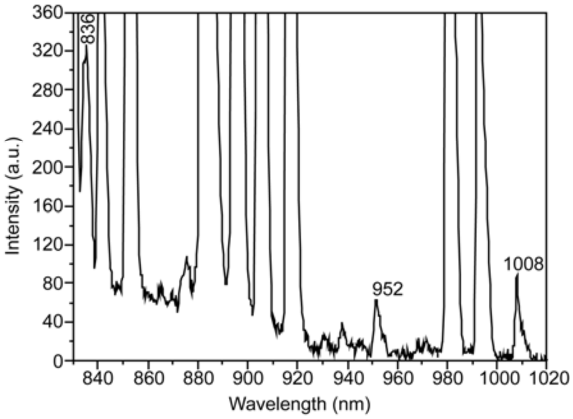

Figure 9 The intensity of 836, 952, 1008 nm.

using the formula [15]:

$$f_{\mathrm{ab}} = -\frac{30.3756}{(2j_{\mathrm{a}}+1)\lambda} |< a \| D \| b >|^2 .$$

The Einstein A coefficients A_{ab} are calculated using the formula [15]:

$$A_{\mathrm{ab}} = \frac{2.02613\times 10^{15}}{\lambda^3}\frac{|< a \| D \| b >|^2}{2j_{\mathrm{a}}+1}.$$

Therefore we have $A_{\mathrm{ab}} = \dfrac{6.67\times 10^{13}}{\lambda^2} f_{\mathrm{ab}}$.

The value of f_{607} and f_{616} is 0.0063 and 0.0124 [15]. The corresponding values of A_{607} and A_{616} are 1.14 and 2.17, respectively.

Table 1 Spectral signal intensities and wavelengths

λ (nm)	I (a.u.)	Transition level	λ (nm)	I (a.u.)	Transition level
Wavelength in order			Intensity in order		
359	61	$7^2P_{3/2}\rightarrow 5^2S_{1/2}$	780	61709	$5^2P_{3/2}\rightarrow 5^2S_{1/2}$
420	1385	$6^2P_{3/2}\rightarrow 5^2S_{1/2}$	795	51131	$5^2P_{1/2}\rightarrow 5^2S_{1/2}$
516	31	$4^2D_{5/2}\rightarrow 5^2S_{1/2}$	827	2724	$7^2F_{7/2}\rightarrow 4^2D_{5/2}$
520	14	$9^2D_{3/2}\rightarrow 5^2P_{1/2}$	420	1385	$6^2P_{3/2}\rightarrow 5^2S_{1/2}$
526	29	$9^2D_{5/2}\rightarrow 5^2P_{3/2}$	762	657	$5^2D_{3/2}\rightarrow 5^2P_{1/2}$
536	51	$8^2D_{3/2}\rightarrow 5^2P_{1/2}$	630	550	$6^2D_{5/2}\rightarrow 5^2P_{3/2}$
539	31	$10^2S_{1/2}\rightarrow 5^2P_{3/2}$	741	357	$7^2S_{1/2}\rightarrow 5^2P_{3/2}$
543	77	$8^2D_{5/2}\rightarrow 5^2P_{3/2}$	621	316	$6^2D_{3/2}\rightarrow 5^2P_{1/2}$
558	57	$9^2S_{1/2}\rightarrow 5^2P_{1/2}$	728	236	$7^2S_{1/2}\rightarrow 5^2P_{1/2}$
565	144	$7^2D_{3/2}\rightarrow 5^2P_{1/2}$	572	181	$7^2D_{5/2}\rightarrow 5^2P_{3/2}$
572	181	$7^2D_{5/2}\rightarrow 5^2P_{3/2}$	616	153	$8^2S_{1/2}\rightarrow 5^2P_{3/2}$
607	88	$8^2S_{1/2}\rightarrow 5^2P_{1/2}$	565	144	$7^2D_{3/2}\rightarrow 5^2P_{1/2}$
616	153	$8^2S_{1/2}\rightarrow 5^2P_{3/2}$	607	88	$8^2S_{1/2}\rightarrow 5^2P_{1/2}$
621	316	$6^2D_{3/2}\rightarrow 5^2P_{1/2}$	1008	88	$5^2F_{7/2}\rightarrow 4^2D_{5/2}$
630	550	$6^2D_{5/2}\rightarrow 5^2P_{3/2}$	543	77	$8^2D_{5/2}\rightarrow 5^2P_{3/2}$
728	236	$7^2S_{1/2}\rightarrow 5^2P_{1/2}$	952	62	$8^2P_{3/2}\rightarrow 4^2D_{5/2}$
741	357	$7^2S_{1/2}\rightarrow 5^2P_{3/2}$	359	61	$7^2P_{3/2}\rightarrow 5^2S_{1/2}$
762	657	$5^2D_{3/2}\rightarrow 5^2P_{1/2}$	558	57	$9^2S_{1/2}\rightarrow 5^2P_{1/2}$
780	61709	$5^2P_{3/2}\rightarrow 5^2S_{1/2}$	536	51	$8^2D_{3/2}\rightarrow 5^2P_{1/2}$
795	51131	$5^2P_{1/2}\rightarrow 5^2S_{1/2}$	516	31	$4^2D_{5/2}\rightarrow 5^2S_{1/2}$
827	2724	$7^2F_{7/2}\rightarrow 4^2D_{5/2}$	539	31	$10^2S_{1/2}\rightarrow 5^2P_{3/2}$
952	62	$8^2P_{3/2}\rightarrow 4^2D_{5/2}$	526	29	$9^2D_{5/2}\rightarrow 5^2P_{3/2}$
1008	88	$5^2F_{7/2}\rightarrow 4^2D_{5/2}$	520	14	$9^2D_{3/2}\rightarrow 5^2P_{1/2}$

The power (P) of the transition signal between two energy levels can be expressed as $p_\lambda=n_\mu A_{\mu\eta}h\nu$ where λ is the transition wavelength, n_μ is the atom density in the level numbered μ (μ=a, b, c⋯), $A_{\mu\eta}$ is the spontaneous transition probability between μ energy level and η energy level, ν is the transition frequency and h is the Plank constant. The transition studied can be expressed with rate equations clearly as

$$p_{359} = n_j A_{ja} h\nu_{359},$$
$$p_{420} = n_i A_{ia} h\nu_{420},$$
$$p_{607} = n_d A_{dg} h\nu_{607},$$
$$p_{616} = n_d A_{dh} h\nu_{616},$$
$$p_{621} = n_n A_{ng} h\nu_{621},$$
$$p_{630} = n_s A_{sh} h\nu_{630},$$
$$p_{728} = n_c A_{cg} h\nu_{728},$$
$$p_{741} = n_c A_{ch} h\nu_{741},$$
$$p_{762} = n_m A_{mg} h\nu_{762},$$
$$p_{780} = n_h A_{ha} h\nu_{780},$$
$$p_{795} = n_g A_{ga} h\nu_{795}.$$

The spontaneous transition probabilities $A_{\mu\eta}$ and the wavelengths involved in the calculation are listed in Table 2. The calculated results of n_μ/n_h are shown in Table 3.

The population density of the ^{87}Rb atoms in the $5P_{3/2}$ level (|h>) is 0.3% (n_h) according to [12]. Since we know n_h, we can obtain the densities in all the excited states mentioned above.

The calculation results of n_μ are shown in Table 4. From the Table 4, we know that the two values of n_d are 1.11 and 1.02, respectively. The difference of between them is small and relative deviation is 10%. For the same reason, the two values of n_c is also different according to 728 nm and 741 nm. However, the difference between them with a relative deviation of 20% is very big.

Table 2 Spontaneous transition probabilities and wavelengths

$A_{\mu\eta}$ (10^6 s^{-1})	λ (nm)
A_{ja}=0.396	λ_{359}=358.7050 [13]
A_{ia}=1.77	λ_{420}=420.1792 [13]
A_{dg}=1.14	λ_{607}=607.0754
A_{dh}=2.17	λ_{616}=615.9626
A_{ng}=2.948	λ_{621}=620.6309 [13]
A_{sh}=3.712	λ_{630}=629.88325 [13]
A_{cg}=2.02	λ_{728}=727.9996 [14]
A_{ch}=3.87	λ_{741}=740.8173 [14]
A_{mg}=2.12	λ_{762}=761.8933 [14]
A_{ha}=38.1	λ_{780}=780.0268 [13]
A_{ga}=36.1	λ_{795}=794.7603 [13]

Table 3 The calculation results of n_μ/n_h

n_μ/n_h	Value
n_j/n_h	0.043
n_i/n_h	0.259
n_d/n_h	0.037 (according to 607 nm) 0.034 (according to 616 nm)
n_n/n_h	0.053
n_s/n_h	0.074
n_c/n_h	0.067 (according to 728 nm) 0.054 (according to 741 nm)
n_m/n_h	0.187
n_g/n_h	0.89

Table 4 The calculation results of n_μ

n_μ	Value (10^{-4})
n_j	1.29
n_i	7.77
n_d	1.11 (according to 607 nm) 1.02 (according to 616 nm)
n_n	1.59
n_s	2.22
n_c	2.01 (according to 728 nm) 1.62 (according to 741 nm)
n_m	5.61
n_g	26.7
n_h	30 [12]
n_b	5.4 [12]
n_l	10.2 [12]
n_r	9.3 [12]

Because of the lack of other values of the spontaneous radiation probability, some values of n_μ cannot be obtained.

3 Conclusion and discussion

From the Table 4, we know some atoms density of energy level, which indicates that there are enough populations in excited states when the lamp is lit. The atoms density of Rb atoms in excited states varies widely, of which n_h is the biggest, n_g is ranked second and n_l is ranked third. The next is n_r and n_i corresponding to, 516 nm, 420 nm, respectively. The value of n_l corresponds to 1475 nm or 1529 nm (Figure 2). Therefore, in the double resonance optical pumping experiment, the lamp may replace the pumping laser of 420 nm, 516 nm, 1475 nm and 1529 nm. As there is also the population in other excited states, the lamp may replace the pumping laser of other wavelengths. In conclusion, the lamp can be used in specific applications such as the frequency stabilization reference of the laser frequency standard and the excited atoms filters without a pump laser to get populations in the excited states [16,17].

Though lamp can operate in three spectral modes, the population ratio between the excited states of Rb atoms is almost constant. Therefore we do not consider the working mode when the intensity of spectral lines of Rb atoms is measured.

The intensity of spectral lines of Rb atoms from visible light to near-infrared is measured. The population ratio between the excited states is calculated according to the spontaneous transition probabilities. At the same time, the population density of energy level is also obtained.

This work was supported by the National Natural Science Foundation of China (*10874009 and 11074011*).

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